PHENOMENOLOGY OF THE LITTLEST HIGGS MODEL

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The little Higgs idea is a new way to solve the little hierarchy problem by protecting the Higgs mass from quadratically divergent one-loop corrections. In this talk I describe the phenomenology of one particular realization of the little Higgs idea: the "Littlest Higgs" model.

1 Introduction

One of the major motivations for physics beyond the Standard Model (SM) is to resolve the hierarchy and fine-tuning problems between the electroweak scale and the Planck scale. The Higgs boson mass in the SM is quadratically sensitive to the cutoff scale Λ of the SM effective theory via radiative corrections. The quantum-corrected Higgs mass is given at one-loop by

$$m_h^2 = \left(m_h^2\right)_{\rm bare} + \frac{3g^2\Lambda^2}{32\pi^2 m_W^2}\left(m_h^2 + 2m_W^2 + m_Z^2 - \frac{4}{3}N_c\sum_f m_f^2\right). \quad (1)$$

For a high cutoff scale Λ, this cancellation must be fine-tuned; for example, for $\Lambda = 10$ TeV, $(m_h^2)_{\rm bare}$ must be tuned at the 1% level to cancel the radiative corrections. In fact, requiring that the one-loop contributions to the Higgs mass-squared parameter are no more than 10 times the size of the renormalized Higgs mass-squared term (i.e., no more than 10% fine-tuning), leads to the requirement that

$$\Lambda_t \lesssim 2 \text{ TeV}, \qquad \Lambda_{W,Z} \lesssim 5 \text{ TeV}, \qquad \Lambda_H \lesssim 10 \text{ TeV}. \quad (2)$$

What could the cancellation mechanism be? The classic solution is supersymmetry. From the bottom-up point of view, the quadratic divergences in the Higgs mass due to top quark, gauge boson and Higgs loops are canceled by the top squark, gaugino and Higgsino loops, respectively. From the top-down point of view, the Higgs mass is protected by supersymmetry to be one loop factor below the soft supersymmetry breaking scale. Thus weak scale supersymmetry is natural if $M_{SUSY} \sim \mathcal{O}(1 \text{ TeV})$.

The little Higgs idea [1] is an alternative way to keep the Higgs boson naturally light. The basic idea is as follows (see Fig. 1):

(i) The Higgs field is a pseudo-Nambu-Goldstone boson [3] of a global symmetry that is spontaneously broken at a scale $\Lambda \sim 4\pi f \sim 10 - 30$ TeV;

(ii) The quadratic divergences in the Higgs mass are canceled at the one-loop level by new particles with masses $M \sim gf \sim 1 - 3$ TeV;

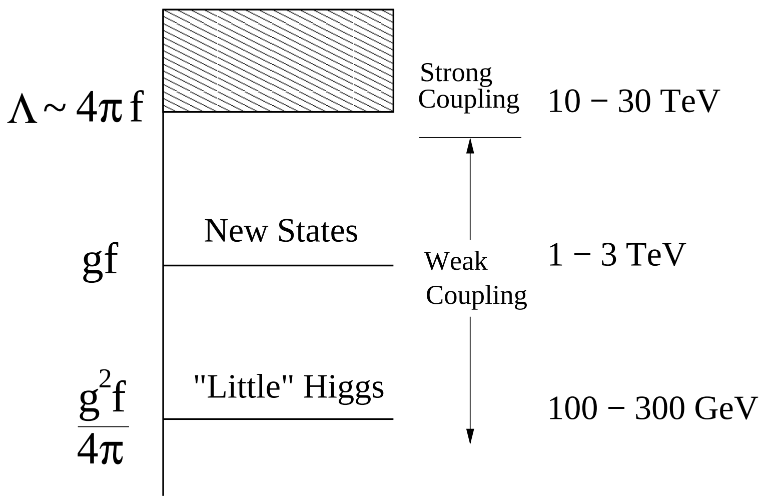

Figure 1. An illustration of the scales in the little Higgs picture. From [2].

(iii) The Higgs acquires a mass radiatively at the electroweak scale $v \sim g^2 f/4\pi \sim 100-300$ GeV.

From the bottom-up point of view, the quadratic divergences in the Higgs mass are canceled by loops of new particles of the same statistics (in contrast to supersymmetry, in which the cancellations are due to particles of opposite statistics). From the top-down point of view, the Higgs mass is protected by the global symmetry. Little Higgs models [1,4,5,6,7,8,9,10] are constructed so that at least two operators are needed to explicitly break all of the global symmetry that protects the Higgs mass. This forbids quadratic divergences at one-loop; the Higgs mass is then smaller than Λ by not one but two loop factors, leading to the little hierarchy $\Lambda \gg f \gg v$.

In this talk I start by reviewing the Littlest Higgs model [5] in Sec. 2, then give an overview of its phenomenology in Sec. 3. Section 4 contains an outlook and conclusions. This talk is based on [11,12].

2 The Littlest Higgs Model

To study phenomenology we must specify a model. We consider here a specific realization of the little Higgs idea called the "Littlest Higgs" model [5], introduced last year by Arkani-Hamed, Cohen, Katz and Nelson.

The Littlest Higgs model is a nonlinear sigma model with a global SU(5)

symmetry group broken down to SO(5) by the vacuum expectation value (vev)

$$\Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}. \tag{3}$$

An $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$ subgroup of SU(5) is gauged; Σ_0 breaks this gauge symmetry down to the diagonal SU(2)×U(1) subgroup, which is identified with the SM gauge group. The symmetry breaking leads to $24 - 10 = 14$ Goldstone bosons, four of which are eaten by the broken gauge generators. The remaining ten Goldstone bosons transform under the SM gauge symmetry as a complex doublet h (which will become the SM Higgs doublet) and a complex triplet ϕ. The Goldstone bosons can be written as $\Sigma = \exp(2i\Pi/f)\Sigma_0$, where $f \sim \Lambda/4\pi$ is the "pion decay constant" that will set the scale of the new particle masses. The uneaten Goldstone bosons are given by

$$\Pi = \begin{pmatrix} & h^\dagger/\sqrt{2} & \phi^\dagger \\ h/\sqrt{2} & & h^\star/\sqrt{2} \\ \phi & h^{\mathrm{T}}/\sqrt{2} & \end{pmatrix}, \quad h = (h^+,\ h^0), \quad \phi = \begin{pmatrix} \phi^{++} & \phi^+/\sqrt{2} \\ \phi^+/\sqrt{2} & \phi^0 \end{pmatrix}. \tag{4}$$

2.1 Gauge sector

The gauge couplings break the global symmetry explicitly. However, the model is constructed such that no single interaction breaks all the global symmetry protecting the Higgs mass. This implements the little Higgs mechanism: at least two interactions are required to break all the global symmetry and give mass to the Higgs, thus forbidding quadratically divergent radiative corrections at the one loop level.

The gauge generators are chosen to be

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & & \\ & & \\ & & \end{pmatrix}, \qquad Q_2^a = \begin{pmatrix} & & \\ & & \\ & & -\sigma^a/2 \end{pmatrix},$$
$$Y_1 = \mathrm{diag}(-3,-3,2,2,2)/10, \qquad Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10, \tag{5}$$

with gauge couplings g_1, g_2, g_1', and g_2', respectively. The generators Q_1^a and Y_1 preserve a global $\mathrm{SU}(3)_1$ symmetry while the generators Q_2^a and Y_2 preserve a second global $\mathrm{SU}(3)_2$ symmetry, each of which forbids a mass for h:

$$SU(3)_1 = \left(\begin{array}{c|c} 0_{2\times 2} & \\ \hline & V_3 \end{array}\right), \qquad SU(3)_2 = \left(\begin{array}{c|c} V_3 & \\ \hline & 0_{2\times 2} \end{array}\right). \tag{6}$$

The Σ_0 vev gives mass to one linear combination of the two SU(2) gauge bosons W_1 and W_2 and to one linear combination of the two U(1) gauge

bosons B_1 and B_2 as follows:

$$\begin{aligned} W'^a &= -cW_1^a + sW_2^a, & M_{W'} &= \frac{gf}{2sc}, \\ B' &= -c'B_1 + s'B_2, & M_{B'} &= \frac{g'f}{2\sqrt{5}s'c'}, \end{aligned} \tag{7}$$

where we define the mixing angles $c, s \equiv \cos\theta, \sin\theta$ and $c', s' \equiv \cos\theta', \sin\theta'$ in terms of the gauge couplings by

$$g = g_1 s = g_2 c, \qquad g' = g_1' s' = g_2' c'. \tag{8}$$

The cancellation of the quadratic divergence in the Higgs mass from gauge boson loops can now be seen explicitly by examining the Lagrangian. The couplings of gauge boson pairs to $h^\dagger h$ arises only through collective breaking, which ensures the cancellation of the divergence:

$$\begin{aligned} \mathcal{L} &= \frac{1}{4}\left(g_1 g_2 W_1^a W_2^a + g_1' g_2' B_1 B_2\right) h^\dagger h + \cdots \\ &= \frac{1}{4}\left[g^2\left(W^a W^a - W'^a W'^a\right) + g'^2\left(BB - B'B'\right)\right] h^\dagger h + \cdots . \end{aligned} \tag{9}$$

The coupling of $h^\dagger h$ to pairs of heavy and light gauge bosons are equal in magnitude and opposite in sign, leading to the cancellation of the quadratic divergence from the SM gauge boson loops by the corresponding heavy gauge bosons.

After electroweak symmetry breaking, the heavy gauge bosons mix with the SM gauge bosons at order v^2/f^2 and form the mass eigenstates W_H, Z_H, A_H.

2.2 Top sector

To cancel the quadratic divergence due to the top quark loop, the Higgs coupling to the top quark must also be generated through collective breaking. This can be done by introducing a vector-like pair of colored Weyl fermions $\tilde{t}$ and $\tilde{t}'^c$, and writing the following couplings:

$$\mathcal{L}_{\rm Yuk} = \frac{\lambda_1}{2} f \epsilon_{ijk}\epsilon_{xy} Q_i \Sigma_{jx}\Sigma_{ky} u_3'^c + \lambda_2 f \tilde{t}\tilde{t}'^c + \text{h.c.}, \tag{10}$$

where the third-generation quark doublet is expanded to $Q = (b, t, \tilde{t})$ [5]. (For an alternative top sector, see [13].) Here $i, j, k = 1, 2, 3$ and $x, y = 4, 5$. The first term in Eq. 10 generates the Higgs couplings to fermions when Σ is expanded in powers of the Goldstone bosons. It is symmetric under the global $SU(3)_2$ symmetry defined in Eq. 6, thus ensuring that the quadratic divergences cancel between the top loop and a loop of the new heavy fermion. The second term in Eq. 10 is a mass term for the vector-like quark. This term preserves the

	Q	u'^c	d^c	L	e^c	$\tilde{t}$	$\tilde{t}'^c$
Y_1	$-\frac{3}{10} - y_u$	y_u	$\frac{3}{5} + y_u$	$\frac{3}{10} - y_e$	y_e	$\frac{1}{5} - y_u$	$-\frac{1}{5} + y_u$
Y_2	$\frac{7}{15} + y_u$	$-\frac{2}{3} - y_u$	$-\frac{4}{15} - y_u$	$-\frac{4}{5} + y_e$	$1 - y_e$	$\frac{7}{15} + y_u$	$-\frac{7}{15} - y_u$

Table 1. Fermion charges under the two U(1) gauge symmetries.

global $SU(3)_1$ symmetry of Eq. 6. Inserting the Σ_0 vev, $\tilde{t}$ marries a linear combination of $\tilde{t}'^c$ and $u_3'^c$ and gets a mass of order f,

$$M_T = f\sqrt{\lambda_1^2 + \lambda_2^2}. \tag{11}$$

The remaining linear combination becomes the right-handed top quark. The top quark mass is given by

$$m_t = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} v. \tag{12}$$

Note that m_t vanishes if either λ_1 or λ_2 is zero: this is a manifestation of the collective breaking.

2.3 The rest of the fermions

There is no need to cancel the quadratic divergences in the Higgs mass due to light fermion loops because they do not become important until scales much higher than the 10 TeV cutoff of the nonlinear sigma model. Thus we can generate masses for the rest of the fermions by writing terms of the same form as Eq. 10, but without the extra vector-like quarks. For the down-type fermion masses, Σ is replaced by Σ^*.

If we make this choice for the light fermion masses, then gauge invariance of the Lagrangian in Eq. 10 fixes the charges of the fermions under the two U(1) gauge symmetries up to only two free continuous parameters y_u and y_e per generation (see Table 1). Imposing anomaly cancellation then fixes the U(1) charges uniquely, requiring:

$$y_u = -2/5, \qquad y_e = 3/5. \tag{13}$$

Different U(1) charges are possible for the light fermions if their masses are instead generated by higher-dimensional operators.

2.4 Higgs potential and electroweak symmetry breaking

The Higgs potential is generated radiatively by integrating out the heavy gauge bosons and heavy top-partner. It can be written in the general form,

$$V = \lambda_{\phi^2} f^2 \mathrm{Tr}(\phi^\dagger \phi) + i\lambda_{h\phi h} f \left(h\phi^\dagger h^T - h^* \phi h^\dagger \right) - \mu^2 h h^\dagger + \lambda_{h^4} (hh^\dagger)^2. \tag{14}$$

The one-loop contributions to λ_{ϕ^2}, $\lambda_{h\phi h}$ and λ_{h^4} are quadratically sensitive to the cutoff Λ. We thus introduce order-one coefficients a, a' to parameterize our

Particle	A_H	Z_H, W_H	$\Phi^0, \Phi^P, \Phi^+, \Phi^{++}$	T
Mass	$f \frac{m_Z s_W}{v\sqrt{5}s'c'}$	$f \frac{m_W}{vsc}$	$f \frac{\sqrt{2}m_H}{v\sqrt{1-(4v'f/v^2)^2}}$	$f\sqrt{\lambda_1^2+\lambda_2^2}$
Mass lower bound	$0.16f$	$0.65f$	$0.66f$	$1.42f$

Table 2. The new particles of the Littlest Higgs model and their masses to leading order in v/f. The masses given all receive corrections of order v^2/f. For M_ϕ, we obtain the lower bound by assuming $m_H \geq 115$ GeV.

ignorance of cutoff-scale physics in the gauge and fermion loops, respectively. We then have,

$$\begin{aligned}
\lambda_{\phi^2} &= \frac{a}{2}\left[\frac{g^2}{s^2c^2} + \frac{g'^2}{s'^2c'^2}\right] + 8a'\lambda_1^2, \\
\lambda_{h\phi h} &= -\frac{a}{4}\left[g^2\frac{(c^2-s^2)}{s^2c^2} + g'^2\frac{(c'^2-s'^2)}{s'^2c'^2}\right] + 4a'\lambda_1^2, \\
\lambda_{h^4} &= \frac{a}{8}\left[\frac{g^2}{s^2c^2} + \frac{g'^2}{s'^2c'^2}\right] + 2a'\lambda_1^2 = \frac{1}{4}\lambda_{\phi^2}.
\end{aligned} \tag{15}$$

The parameter μ^2 gets log-divergent contributions at one-loop and quadratically divergent contributions at two-loop, which are both generically one loop factor smaller than f^2, leading to a Higgs mass of order $g^2 f/4\pi$. Since there will be additional cutoff-scale freedom in the two-loop contributions to μ^2, we regard it as a free parameter. For $\mu^2 > 0$, electroweak symmetry is broken, and both h and ϕ get vevs:

$$2\langle h^0\rangle^2 \equiv v^2 = \frac{\mu^2}{\lambda_{h^4} - \lambda_{h\phi h}^2/\lambda_{\phi^2}}, \qquad \langle i\phi^0\rangle \equiv v' = \frac{\lambda_{h\phi h}}{2\lambda_{\phi^2}}\frac{v^2}{f}. \tag{16}$$

Note that $v' \sim v^2/f$ is much smaller than v.

The scalar masses, to leading order in v/f, are

$$M_\phi^2 = \lambda_{\phi^2} f^2, \qquad m_H^2 = 2\mu^2. \tag{17}$$

2.5 Summary of new parameters and particles

The Littlest Higgs model contains six new free parameters, which we can choose as follows:

(1) $\tan\theta = s/c = g_1/g_2$: new SU(2) gauge coupling.
(2) $\tan\theta' = s'/c' = g_1'/g_2'$: new U(1) gauge coupling.
(3) f: symmetry breaking scale, $\mathcal{O}$(TeV).
(4) v': triplet vev; $v' < v^2/4f$.
(5) m_H: SM Higgs mass.
(6) M_T: top-partner mass (together with m_t, this fixes λ_1 and λ_2).

The new particles and their masses are summarized in Table 2.

3 Phenomenology

There are by now quite a number of little Higgs models in the literature [1,4,5,6,7,8,9,10]. It thus behooves us to look for generic features of the phenomenology. All little Higgs models must contain the following features at the TeV scale:

- New heavy gauge bosons to cancel the W and Z loops. In the Littlest Higgs model these are almost pure SU(2) gauge bosons. The SM fermions must transform under only one of the two gauged SU(2) symmetries – say, $\mathrm{SU}(2)_1$ – so their couplings to the new heavy gauge bosons are universal, $\propto g \cot\theta$. This determines the cross section for Drell-Yan production of the heavy gauge bosons at the LHC. This appears to be a generic feature of "product gauge group" little Higgs models [1,4,5,6,8,10] in which the $\mathrm{SU}(2)_L$ SM gauge group comes from the breaking of two groups down to a diagonal subgroup. The decays of the heavy gauge bosons are more model dependent, since non-fermionic decays can play a role.

- A new heavy fermion to cancel the top quark loop. The production and decay modes of the heavy fermion are fixed by the form of the Yukawa Lagrangian, Eq. 10, which appears in many little Higgs models. Some models contain more than one top-partner and/or partners for the two light fermion generations, although typically only one of these states cancels the top loop divergence.

- New heavy scalars to cancel the Higgs loop. The heavy scalar sector is very model dependent, and can consist of singlets, doublets or triplets. Some models have two light Higgs doublets [4,6,7,8,9].

3.1 Electroweak precision constraints

The constraints on little Higgs models from electroweak precision data have been examined in detail in [14,15,16,17]. The constraints come from Z pole data, low-energy neutrino-nucleon scattering, and the W mass measurement. Together, these measurements probe little Higgs model contributions from the exchange of the heavy gauge bosons between fermion pairs, mixing between the heavy and light gauge bosons that modifies the Z boson couplings to fermions, and a shift in the mass ratio of the W and Z.

The contributions to the various observables in the Littlest Higgs model are outlined in Table 3. Examining these contributions yields a strategy for reducing the impact of the Littlest Higgs model on electroweak observables:

(1) Reduce the triplet vev: $v' \ll v$;

(2) Reduce the heavy SU(2) gauge boson contributions: $c \ll 1$;

(3) Reduce the heavy U(1) gauge boson contributions to M_Z: $c' \approx s'$;

(4) Reduce the heavy U(1) gauge boson contributions to neutral current couplings: $c'^2 Y_1 \approx s'^2 Y_2$.

	$SU(2)_H$	$U(1)_H$	$\langle\phi\rangle$
M_W^2	$-\frac{5}{12}\frac{v^2}{f^2}+c^2s^2\frac{v^2}{f^2}$	0	$4\frac{v'^2}{v^2}$
M_Z^2	$-\frac{5}{12}\frac{v^2}{f^2}+c^2s^2\frac{v^2}{f^2}$	$-\frac{5}{4}\frac{v^2}{f^2}(c'^2-s'^2)^2$	$8\frac{v'^2}{v^2}$
G_F	$\frac{5}{12}\frac{v^2}{f^2}$	0	$-4\frac{v'^2}{v^2}$
$M_Z^2 G_F$	$c^2s^2\frac{v^2}{f^2}$	$-\frac{5}{4}\frac{v^2}{f^2}(c'^2-s'^2)^2$	$4\frac{v'^2}{v^2}$
δg_{ff}	$\propto c^2\frac{v^2}{f^2}$	$\propto(-c'^2Y_1+s'^2Y_2)\frac{v^2}{f^2}$	0

Table 3. Extra contributions to the electroweak parameters in the Littlest Higgs model from the exchange of heavy SU(2) and U(1) gauge bosons and from the triplet vev. δg_{ff} collectively denotes the modification of the neutral current couplings of the SM fermions.

The first three conditions can be straightforwardly satisfied by going to the appropriate parameter region. The fourth condition is more difficult, since it depends on the U(1) charge assignments of (mainly the first two generations of) fermions. It turns out that the charge assignments obtained from requiring that the light fermion mass terms have the same form as those of the third generation (Eq. 10) and imposing anomaly cancellation satisfy the fourth condition reasonably well. These lead to a lower bound on f of about 1 TeV [16], corresponding to a lower bound on M_{W_H}, M_{Z_H} of about 2 TeV. The cancellation in the fourth condition can be improved by requiring the light fermion masses to be generated by appropriate higher-dimensional operators so that their U(1) charges can be chosen with more freedom; however, this is not really necessary to avoid fine-tuning.

The situation can also be simplified by gauging only one U(1) symmetry (i.e., hypercharge), so that there is no heavy U(1) gauge boson and the second column in Table 3 is eliminated. Removing the heavy U(1) gauge boson has the added benefit of avoiding constraints [15] from direct Tevatron Z' searches.

These conclusions can be generalized to other little Higgs models. The lower bounds on the masses of the new heavy gauge bosons are generally in the $1.5-2$ TeV range [16,17]. In models with a product gauge group, the electroweak precision measurements favor parameter regions in which the new heavy gauge bosons are approximately decoupled from the SM fermions; e.g., $\cot\theta \simeq 0.2$.

The electroweak precision measurements do not directly constrain the mass of the top-partner. However, the mass of the top-partner is related to the heavy gauge boson masses by the structure of the model. For naturalness, the top-partner should be as light as possible. The lower bounds on the top-partner mass are generally in the $1-2$ TeV range.

3.2 Collider signatures

Z_H and W_H: The heavy SU(2) gauge bosons Z_H and W_H can be produced

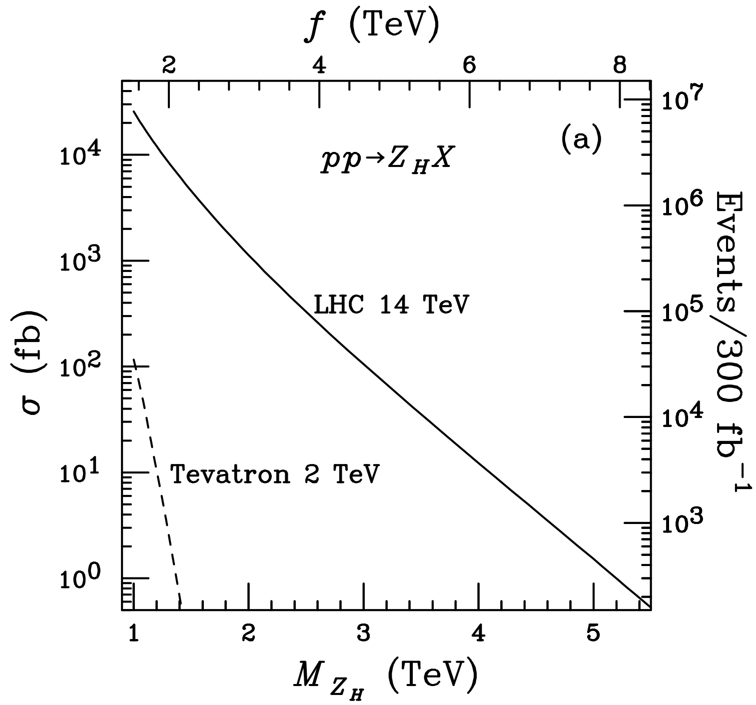

Figure 2. Cross section for Z_H production in Drell-Yan at the LHC and Tevatron, for $\cot\theta = 1$. From [11].

via Drell-Yan at the LHC (and at the Tevatron, if they are light enough). The cross section is proportional to $\cot^2\theta$ because the Z_H and W_H couplings to fermion pairs are proportional to $\cot\theta$. In Fig. 2 we show the cross section for Z_H production at the Tevatron and LHC for $\cot\theta = 1$. In the region of small $\cot\theta \simeq 0.2$ favored by the precision electroweak data, the cross section must be scaled down by $\cot^2\theta \simeq 0.04$. Even with this suppression factor, a cross section of 40 fb is expected at the LHC for $M_{Z_H} \simeq 2$ TeV, leading to 4,000 events in 100 fb^{-1} of data. The production and decay of Z_H and W_H at the LHC has also been studied in [18].

The decay branching fractions of Z_H are shown in Fig. 3.[a] The partial widths to fermion pairs are proportional to $\cot^2\theta$, while the partial widths to ZH and W^+W^- are proportional to $\cot^2 2\theta$. This offers a method to distinguish the Littlest Higgs model from a "big Higgs" model with the same gauge group in which the Higgs doublet transforms under only one of the SU(2) groups [18], in which case the ZH and W^+W^- partial widths would also

[a] Here we correct an error in [11,18] in which the $Z_H \to W^+W^-$ decay mode was overlooked.

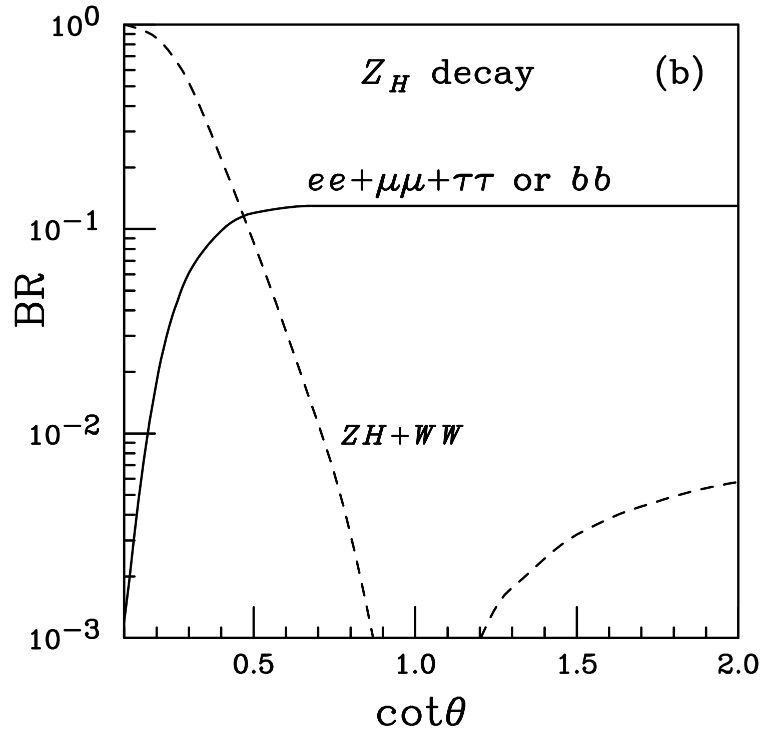

Figure 3. Branching ratios of Z_H into SM particles as a function of $\cot\theta$, neglecting final-state mass effects.

be proportional to $\cot^2\theta$. Neglecting final-state particle masses, the branching fraction into three flavors of charged leptons is equal to that into one flavor of quark ($\simeq 1/8$ for $\cot\theta \gtrsim 0.5$), due to the equal coupling of Z_H to all SU(2) fermion doublets. The branching ratio into ZH is equal to that into W^+W^-. The total width of Z_H depends on $\cot\theta$; for $\cot\theta \sim 0.2$ the Z_H width is about 1% of the Z_H mass.

The $W_H^\pm$ couplings to fermion doublets are larger by a factor of $\sqrt{2}$ than the Z_H couplings; this together with the parton distribution of the proton leads to a $W_H^\pm$ cross section at the LHC about 1.5 times that of Z_H [18]. As for the W_H decays, the branching fraction into three lepton flavors is equal to that into one generation of quarks ($\simeq 1/4$ for $\cot\theta \gtrsim 0.5$). At low $\cot\theta$, $W_H^\pm$ decays predominantly into $W^\pm H$ and $W^\pm Z$ with partial widths proportional to $\cot^2 2\theta$.

The general features of the production and decay of Z_H and W_H should extend to other little Higgs models with "product gauge groups". The decay to ZH will be modified in models that contain more than one light Higgs

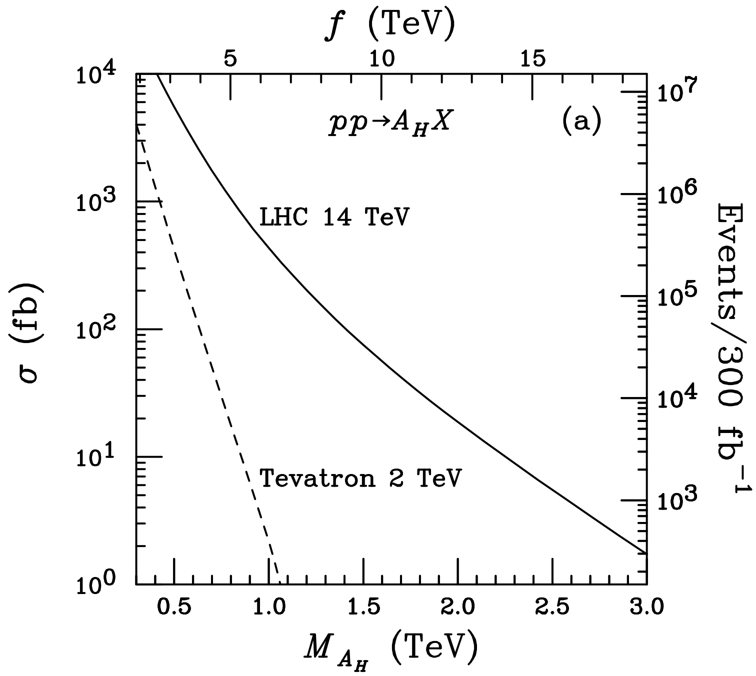

Figure 4. Cross section for A_H production in Drell-Yan at the LHC and Tevatron, for $\cot\theta' = 1$. From [11].

doublet.

A_H: The heavy U(1) gauge boson is the lightest new particle in the Littlest Higgs model. Its couplings to fermions are more model dependent than those of the heavy SU(2) gauge bosons, since they depend on the U(1) charges of the fermions. Even the presence of A_H is model-dependent, since one can remove this particle from the Littlest Higgs model by gauging only one U(1) group (hypercharge) without adding a significant amount of fine-tuning. Nevertheless, we show in Figs. 4 and 5 the cross section and branching ratios[b] of A_H for the anomaly-free choice of U(1) charges discussed in Sec. 2.3.

T: The heavy top-partner T can be pair produced by QCD interactions with model-independent couplings. However, this production mode is suppressed by phase space due to the high mass of T. The single T production mode, $W^+b \to T$, is dominant for M_T above about a TeV. The cross section for single T production depends on the ratio of couplings λ_1/λ_2, which relates M_T to the scale f. The cross sections are shown in Fig. 6. The top-partner T decays into tH, tZ and bW with partial widths in the ratio $1:1:2$.

[b]Here again we correct an error in [11] in which the A_H decay to W^+W^- was overlooked.

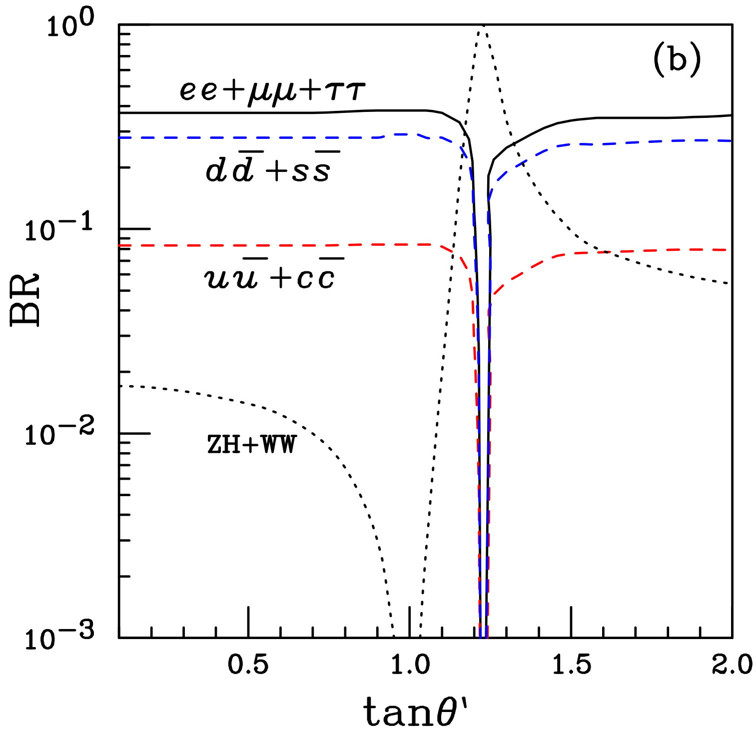

Figure 5. Branching ratios of A_H into fermions and $ZH + WW$ as a function of $\tan\theta'$, neglecting final-state mass effects.

The top sector is quite similar in many of the other little Higgs models in the literature, so that these general features of T production and decay should apply. Some models contain more than one top-partner [6,7,8,10,13], or contain partners for the two light generations of fermions as well [7,9]; in this case the phenomenology will be modified.

Φ^{++}*:* The doubly charged Higgs triplet state Φ^{++} can be singly produced through resonant $W^+W^+ \to \Phi^{++} \to W^+W^+$. The cross section for this process is proportional to v'^2, which may make it difficult to see due to lack of rate. The doubly charged Higgs could also be pair produced if it is not too heavy. The doubly charged Higgs can in principle decay to a pair of like-sign charged leptons via the dimension-four operator $L\Phi L$, offering a more distinctive signature; however, the coupling is highly model dependent and care must be taken to avoid generating too large a neutrino mass from the triplet vev.

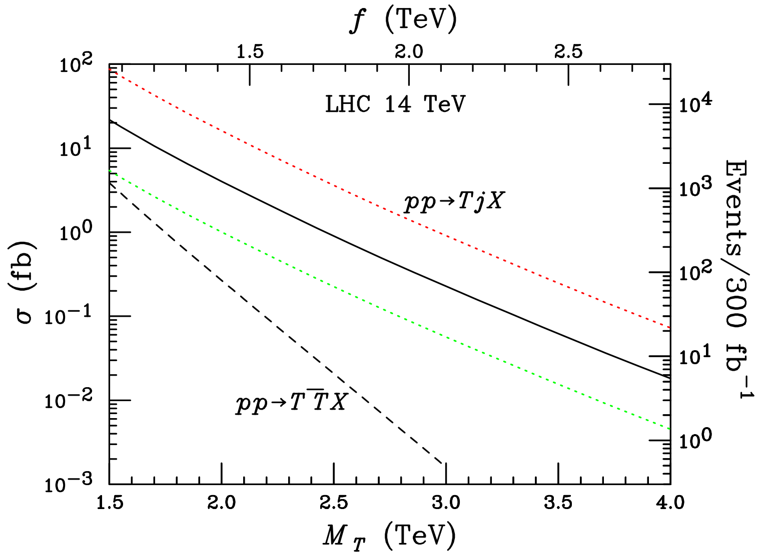

Figure 6. Cross sections for T production at the LHC. The single T cross section is shown for $\lambda_1/\lambda_2 = 1$ (solid) and $\lambda_1/\lambda_2 = 2$ (upper dotted) and $1/2$ (lower dotted). The QCD pair production cross section is shown for comparison (dashed). From [11].

3.3 Future precision measurements

As already explained, little Higgs models modify the precision electroweak observables, so that a significant improvement in the measurements of these observables (at, for example, a "Giga-Z" machine) should turn up a signal. However, there are other precision measurements in which the little Higgs should show its effects. Here we discuss the effects of the Littlest Higgs model on triple gauge couplings [11] and loop-induced Higgs decays into gluon and photon pairs [12]. The effects of the Littlest Higgs model on $b \to s\gamma$ [19], the muon anomalous magnetic moment [20], and double-Higgs production via gluon fusion [21] have also been studied in the literature.

Triple gauge couplings: The WWZ triple gauge boson coupling in the Littlest Higgs model is modified from its SM form due to the modification of G_F by W_H exchange:

$$g_1^Z = \kappa_Z = 1 + \frac{1}{\cos 2\theta_W} \left\{ \frac{v^2}{8f^2} \left[-4c^2s^2 + 5(c'^2 - s'^2)^2 \right] - \frac{2v'^2}{v^2} \right\}, \qquad (18)$$

where the form-factors are defined according to

$$\mathcal{L}_{WWV} = i g_{WWV} \left[g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \right.$$

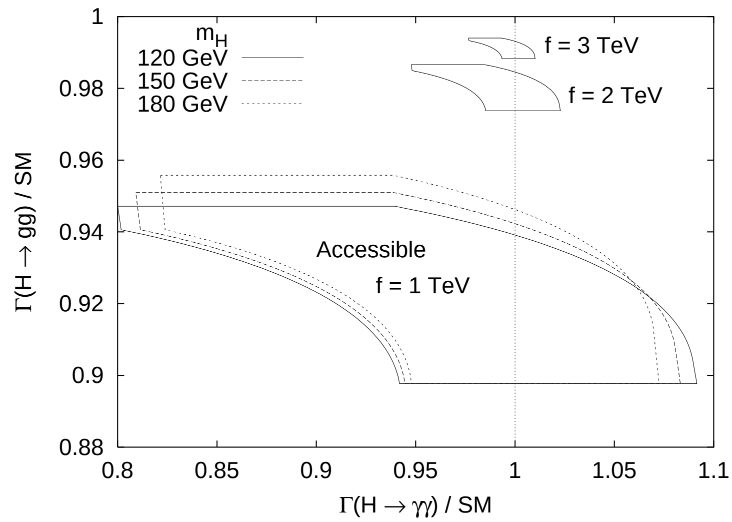

Figure 7. Range of values of $\Gamma(H \to gg)$ versus $\Gamma(H \to \gamma\gamma)$ accessible in the Littlest Higgs model normalized to the SM value, for m_H = 120, 150, 180 GeV and f = 1, 2, 3 TeV. From [12].

$$+\frac{\lambda_V}{m_W^2} W_\mu^{+\nu} W_\nu^{-\rho} V_\rho^\mu \Big] . \tag{19}$$

At present, the constraints from the WWZ coupling are weak compared to those from electroweak precision measurements. However, at a future linear collider, a precision of $10^{-3} - 10^{-4}$ on g_1^Z and κ_Z should be reachable; this would be sensitive to $f \sim (15-50)v \sim 3.5 - 12$ TeV for generic parameter values. Unfortunately for this measurement, in the region of parameter space in which the electroweak precision bounds are loosened (small c and v' and $c' \simeq s'$) the modification to g_1^Z and κ_Z is also suppressed.

Loop-induced Higgs decays: The Higgs decays into gluon pairs or photon pairs will be modified in the Littlest Higgs model by the new particles running in the loop and by the shifts in the Higgs couplings to the SM W boson and top quark due to the structure of the model. These modifications of the Higgs couplings to gluon or photon pairs scale like $1/f^2$, and thus decouple at high f scales. The range of partial widths as a function of f accessible by varying the other model parameters are shown in Fig. 7.

Are these corrections observable? For $f \geq 1$ TeV, the correction to $\Gamma(H \to gg)$ is always less than 10%. This is already smaller than the remaining SM theoretical uncertainty on the gluon fusion cross section due to uncalculated higher-order QCD corrections. For the partial width to photons, the situation is more promising because the QCD corrections are well under control. At the LHC, the $H \to \gamma\gamma$ decay rate can be measured to 15-20%; this probes

$f < 1.0$ TeV at 1σ. A linear e^+e^- collider has only comparable precision since the $H \to \gamma\gamma$ branching ratio measurement is limited by statistics. The most promising measurement would be done at a photon collider, in which the $\gamma\gamma \to H \to b\bar{b}$ rate could be measured to about 2%. Combining this with a measurement of the branching ratio of $H \to b\bar{b}$ to about 1.5-2% at the e^+e^- collider allows the extraction of $\Gamma(H \to \gamma\gamma)$ with a precision of about 3%. Such a measurement would be sensitive to $f < 2.7$ TeV at the 1σ level, or $f < 1.8$ TeV at the 2σ level. A 5σ deviation is possible for $f < 1.2$ TeV. For comparison, the electroweak precision constraints require $f \gtrsim 1$ TeV in the Littlest Higgs model.

The biggest model dependence in the loop-induced Higgs decays in little Higgs models comes from the content of the Higgs sector at the electroweak scale. In models with only one light Higgs doublet, our general conclusions should hold, up to factors related to the multiplicity and detailed couplings of the new heavy particles. However, many little Higgs models [4,6,7,8,9] contain two light Higgs doublets. In this case, mixing between the two neutral CP-even Higgs particles and the contribution of a relatively light charged Higgs boson running in the loop can lead to large deviations in the couplings of the lightest Higgs boson to gluon or photon pairs, swamping the effects from the heavy states.

4 Outlook and Conclusions

The little Higgs idea provides a new way to address the little hierarchy problem of the Standard Model by making the Higgs a pseudo-Nambu-Goldstone boson of a spontaneously broken global symmetry. The global symmetry is explicitly broken by gauge and Yukawa interactions; however, no single interaction breaks all the symmetry protecting the Higgs mass. This prevents quadratically divergent radiative corrections to the Higgs mass from appearing at the one-loop level, and thus allows the cutoff scale to be pushed higher by one loop factor, to ~ 10 TeV.

From the bottom-up point of view, the quadratically divergent radiative corrections to the Higgs mass due to top quark, gauge boson, and Higgs loops are canceled by new heavy quarks, gauge bosons and scalars, respectively. In contrast to supersymmetry, the cancellations occur between loops of particles with the *same* statistics.

The details of the phenomenology depend on the specific model. Since quite a few little Higgs models have already appeared on the market over the past two years, finding generic features of the phenomenology is important. Very generically, there must be new gauge bosons, fermions and scalars to cancel the quadratic divergences in the Higgs mass. Less generically, models with product gauge groups of the form $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$ contain an SU(2) triplet of new heavy gauge bosons, $Z_H, W_H^{\pm}$.

There is some tension between the precision electroweak constraints push-

ing up the new particle masses and the requirement that the new particles be light to avoid fine tuning. However, by tuning the parameters of the models appropriately one can satisfy both constraints. This tuning of the parameters should be explained in the ultraviolet completion of the nonlinear sigma model. Our developing understanding of the effects of little Higgs models on the electroweak precision observables is now driving model building to incorporate features that loosen the constraints. Taking these constraints into account, the new particles should live in the $1-2$ TeV mass range and should be accessible at the LHC.

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